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Summary

An investigation was conducted to examine the erosion behavior of uncoated and coated polymer matrix composite (PMC) specimens subjected to solid particle impingement using air jets. The PMCs were carbon-Kevlar (DuPont, Wilmington, DE) fiber-epoxy resin composites with a temperature capability up to 393 K (248 °F). Tungsten carbide-cobalt (WC-Co) was the primary topcoat constituent. Bondcoats were applied to the PMC substrates to improve coating adhesion; then, erosion testing was performed at the University of Cincinnati. All erosion tests were conducted with Arizona road-dust (ARD), impinging at angles of 20° and 90° on both uncoated and two-layer coated PMCs at a velocity of 229 m/s and at a temperature of 366 K (200 °F). ARD contains primarily 10-μm aluminum oxide powders. Vertically scanning interference microscopy (noncontact, optical profilometry) was used to evaluate surface characteristics, such as erosion wear volume loss and depth, surface topography, and surface roughness. The results indicate that noncontact, optical interferometry can be used to make an accurate determination of the erosion wear volume loss of PMCs with multilayered structures while preserving the specimens. The two-layered (WC-Co topcoat and metal bondcoat) coatings on PMCs remarkably reduced the erosion volume loss by a factor of approximately 10. The tenfold increase in erosion resistance will contribute to longer PMC component lives, lower air friction, reduced related breakdowns, decreased maintenance costs, and increased PMC reliability. The decrease in the surface roughness of the coated vanes will lead to lower air friction and will subsequently reduce energy consumption. Eventually, the coatings could lead to overall economic savings.

Introduction

Polymer matrix composites (PMCs) are facing higher performance requirements and increasingly greater use in aerospace and automotive applications because of their light weight and high strength-to-weight ratios relative to metals (refs. 1 to 3). These materials, however, have had limited use replacing metals in propulsion applications because PMCs have poor abrasion and oxidation resistance, which contributes to short product lives and restricts their use, especially at high temperatures.

Surface coatings may open up possibilities by making PMCs resistant to erosion wear, sliding wear, and oxidation (ref. 4). Hard coatings have been especially useful in applications involving erosive and abrasive wear. However, simply applying a hard metallic or ceramic coating on softer, tough PMCs

to improve erosion and abrasion resistance is not effective since coating durability may be short lived. Increased hardness is usually concomitant with decreasing adherence and toughness. Because PMCs generally have higher coefficients of thermal expansion than metallic or ceramic coatings, adhesion strength at the interface between a coating and a substrate may be poor.

One technique commonly used to improve coating adhesion or durability is the use of bondcoats that are interleaved between a coating (topcoat) and a substrate with vastly different coefficients of thermal expansion. Bondcoats sandwiched between high-quality plasma-sprayed, erosion-resistant coatings (topcoats) and PMC substrates substantially improved the erosion resistance of PMCs (refs. 4 and 5). Chambers et al. (ref. 5) showed that chromium was a suitable interface layer for improved erosion resistance when hard coatings such as ZrB_2 were deposited on polyimide substrates. They reported that use of titanium interface layers under TiC/Ni coatings on polyimide, however, was not successful. Thus, the multicomponent composition of topcoat-bondcoat-PMC must be optimized for the erosion protection of PMCs.

There has been no easy, accurate way to measure the erosion wear loss produced on a multilayered (topcoat/bondcoat) system. An even more subtle, yet critical, problem is that these erosion coatings contain two or more materials with different densities. Therefore, simply measuring the specimen mass loss before and after erosion will not provide an accurate gauge of the volume losses of the multilayered coating system. Consequently, erosion wear volume losses have been obtained by measuring cross-sectional areas, determined from stylus tracings using stylus profilometry, across the wear scars. Also, coating wear volumes have been determined from cross sectioning the wear scars and observing the cross sections by optical microscopy (ref. 4). Both techniques are time-consuming. Wear measurement by optical microscopy requires sample destruction and does not provide a comprehensive measure of the entire wear volume loss.

Vertically scanning interference microscopy (also called noncontact, optical profilometry; noncontact, vertical-scanning, white-light interferometry; or noncontact, vertical scanning, laser interferometry) can profile an extremely wide range of surface heights and can measure surface features without contact while preserving the sample (ref. 6). It characterizes and quantifies surface roughness, step height, bearing ratio, height distribution, critical dimensions (such as area and volume of damage, eroded craters, and wear scars), and other topographical features. It has three-dimensional profiling capability with excellent precision and accuracy; for example, profile heights ranging from <1 nm to $1000\text{ }\mu\text{m}$ at speeds to $10\text{ }\mu\text{m/sec}$ with 0.1-nm height resolution, and large profile areas to 50 by 50 mm or 100 by 100 mm.

This investigation was conducted to examine the erosion behavior of uncoated and two-layer-coated PMC specimens subjected to solid particle impingement using air jets. Also, two methods—the stitching method and the depth-measuring method—of determining the erosion volume loss using noncontact optical interferometry were evaluated. The PMCs were carbon-Kevlar (DuPont, Wilmington, DE) fiber-epoxy resin composites with a temperature capability up to 393 K ($248\text{ }^\circ\text{F}$). Tungsten carbide-cobalt (WC-Co) was the primary topcoat constituent. Bondcoats were applied to the PMC substrates to improve coating adhesion; then, erosion testing was performed at the University of Cincinnati. All erosion tests were conducted with Arizona road-dust (ARD), which contains primarily $10\text{-}\mu\text{m}$ aluminum oxide powders, impinging at angles of 20° and 90° on both uncoated and coated PMCs at a velocity of 229 m/s and at a temperature of 366 K ($200\text{ }^\circ\text{F}$). Noncontact, white-light, optical profilometry was used to evaluate surface characteristics, such as erosion volume loss and depth, surface topography, and surface roughness.

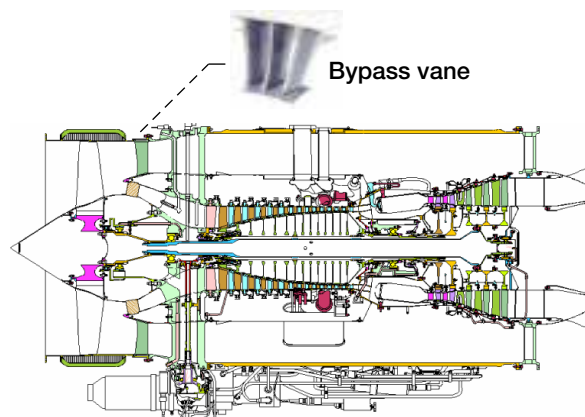


Figure 1.—AE 3007 (Allison Engine Company) fan: location of bypass vanes.

Materials

The materials are described in detail in reference 7. Briefly, a coating system was applied to carbon-Kevlar fiber-epoxy resin composite engine components (the AE 3007 fan bypass vanes (Allison Engine Company) shown in fig. 1) with a temperature capability up to 393 K (248 °F). The coating included a bondcoat applied to the PMC substrate followed by a hard topcoat. The bondcoat with no polymer has a coefficient of thermal expansion that bridged the coefficient of thermal expansion of the PMC and the topcoat to improve adhesion to the PMC substrate. WC-Co was the primary topcoat constituent.

Experimental Procedure

Coating Process

The coating process was adapted from production coating methods. Prior to coating, the vanes were carefully grit-blasted with alumina to prepare the surface for deposition. A combustion spray gun with oxygen/acetylene gas was used to apply the bondcoat. Coating trials were conducted with the part being held stationary or rotated with the gun moving vertically through an automated ladder-step control program. The topcoat was applied to the bondcoat using a plasma spray gun. Further details of the coating process are described in reference 7.

Erosion Rig Test Procedure

Specimens (12.5 by 18.5 mm) were cut from the coated AE 3007 fan bypass vanes at a set trailing edge location and placed in the test fixture (fig. 2). The fixture was designed to accommodate specimen curvature and to retain uneroded edge area for a nondestructive evaluation baseline after the erosion test.

Erosion testing was performed at the University of Cincinnati erosion rig facility (fig. 3). In addition to providing high temperatures, this facility realistically simulates all the erosion parameters that are deemed to be important from an aerodynamic point of view (refs. 8 and 9). These parameters include particle velocity, impingement angle, erodent particle size and type, and specimen size. Varying the airflow in the erosion rig wind tunnel controlled the particle velocities. Rotating the specimen fixture relative to the flow stream direction set the particle impingement angles. Impingement angles in erosion

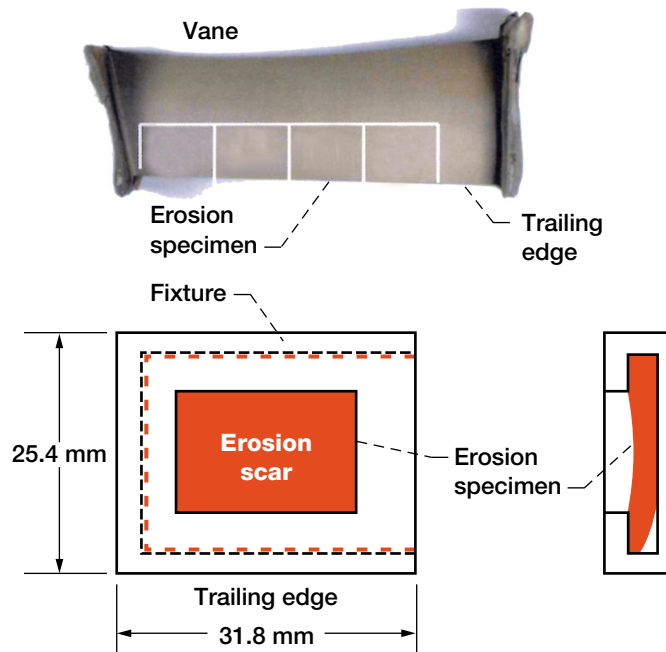


Figure 2.—Erosion specimen, fixture, and inserted erosion specimen.

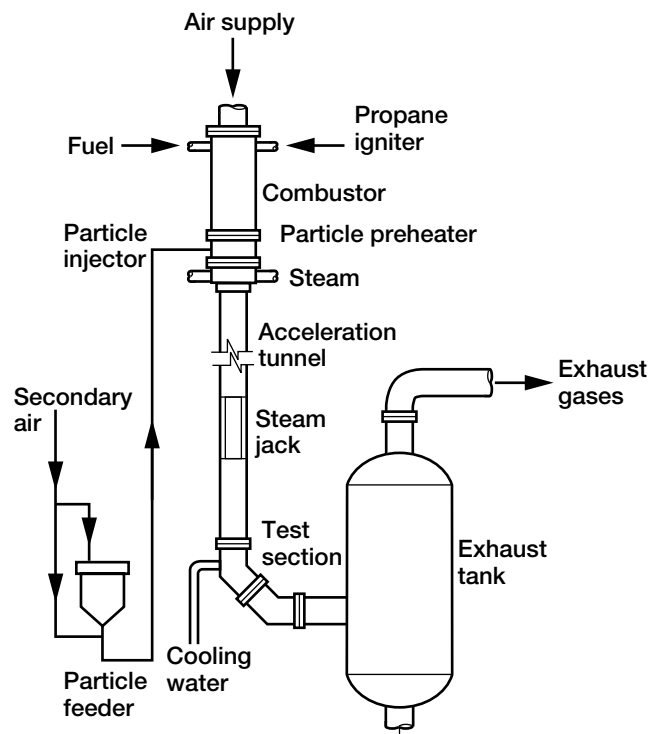


Figure 3.—University of Cincinnati's hot erosion rig.

are defined relative to the plane of the specimen fixture. Heating the flow with a combustible hydrocarbon gas or steam jacket controlled the coated PMC specimen temperature. The erosion test procedure, which used ARD impinging at angles of 20° and 90° with 15 and 10 g of ARD, respectively, was used on both uncoated and coated vane specimens at a velocity of 229 m/s at 366 K (200 °F). This procedure is also described in reference 7.

Coating Effectiveness Analysis Procedure

Erosion wear volume loss was determined by using noncontact, optical profilometry (Veeco Corporation, Tucson, AZ). This method characterizes and quantifies surface roughness, height distribution, critical dimensions (such as area and volume of the damaged erosion wear scars), and topographical features. It has three-dimensional profiling capability with excellent precision and accuracy (e.g., profile heights ranging from ≤ 1 nm up to $1000\text{ }\mu\text{m}$ with 0.1-nm height resolution). The shape of a surface can be displayed by a computer-generated map developed from digital data derived from a three-dimensional interferogram of the surface. In this investigation, all measurements were made with an effective magnification of $\times 2.5097$ (a $\times 5$ magnification objective and a $\times 0.5$ eyepiece) that profiled an effective field-of-view with a 1.875- by 2.463-mm area and height sampling up to $1000\text{ }\mu\text{m}$ for vane coupon specimens and height sampling of $50\text{ }\mu\text{m}$ for the step-height measurement standard.

Step-height measurement standard.—First, the measurement effectiveness of the noncontact optical profilometry was verified with a step-height measurement standard that has a rectangular groove ($10\text{ }\mu\text{m}$ deep by $1000\text{ }\mu\text{m}$ wide by $5000\text{ }\mu\text{m}$ long). Figures 4(a) and (b) show typical three-dimensional contour maps of part of the groove and the whole rectangular groove and its surroundings, respectively. Figure 4(a) is the contour map obtained from a single measurement, whereas figure 4(b) is the contour map that was obtained using the stitching method.

For the stitching method, continuous measurements were made over the rectangular groove and its surroundings. Then, these measurement data were stitched together to give the contour map shown in figure 4(b). After stitching, volume analyses were conducted with the stitched contour maps. The mean value and standard deviation of the volume of the rectangular groove were obtained from four stitched contour maps, which were from measurements taken on different days. The volume of the rectangular groove was computed directly.

For the depth-measuring method, two-dimensional cross-sectional profiles of the step-height standard (rectangular groove) were taken. Examples of the two-dimensional, cross-sectional profiles of the rectangular groove are shown in figures 5(a) and (b). The depths of the rectangular groove were obtained at eight locations. Then, the volume of the rectangular groove was calculated simply by using the mean value of each of the measured depths, long sides, and short sides of the rectangular groove.

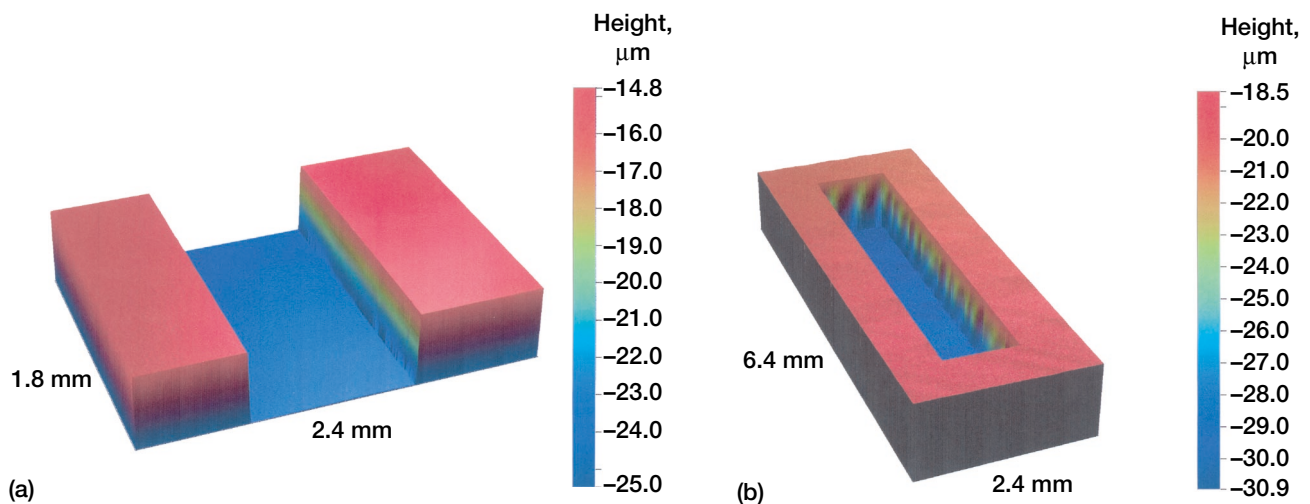


Figure 4.—Three-dimensional contour maps of a step-height measurement standard. (a) Part of the rectangular groove and its surroundings. (b) Whole rectangular groove and its surroundings.

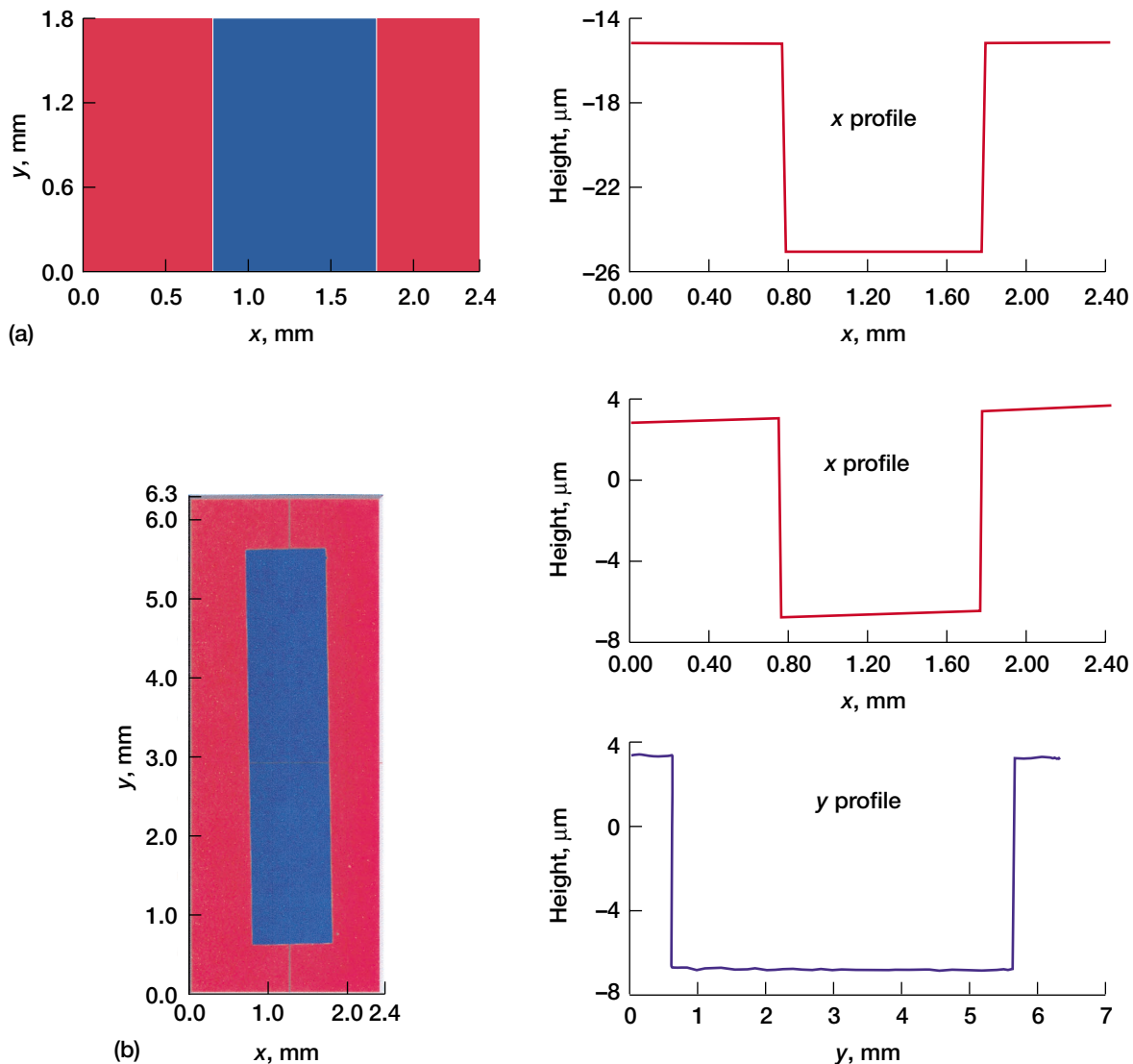


Figure 5.—Depth profile of a step-height measurement standard. (a) Part of the rectangular groove and its surroundings. (b) Whole rectangular groove and its surroundings.

Vane coupon specimens.—Two noncontact, optical profilometry methods were used to determine the erosion wear volume loss of the uncoated and coated specimens: the stitching method and the depth-measuring method.

For the stitching method, the concave surface of the as-received, uneroded specimen was sampled and measured. Continuous measurements were conducted over a given area. These measurements were stitched together to give a larger sampling area of a specimen (e.g., the 12 by 24 mm area in fig. 6).

Before erosion, a given area (e.g., 12.5 by 18 mm) of the uneroded vane coupon specimen was analyzed with the noncontact optical profiler (fig. 7(a)). The measurement data were stitched together to give a plot of the stitched area with surface statistics. The natural volume of the stitched area, in which the as-received surface before erosion would hold if it were covered just to the nominal surface of highest peak, was obtained (fig. 7(b)). In other words, the volume necessary to submerge the stitched area of the vane coupon specimen surface was calculated. This calculated volume is designated V_1 in this investigation.

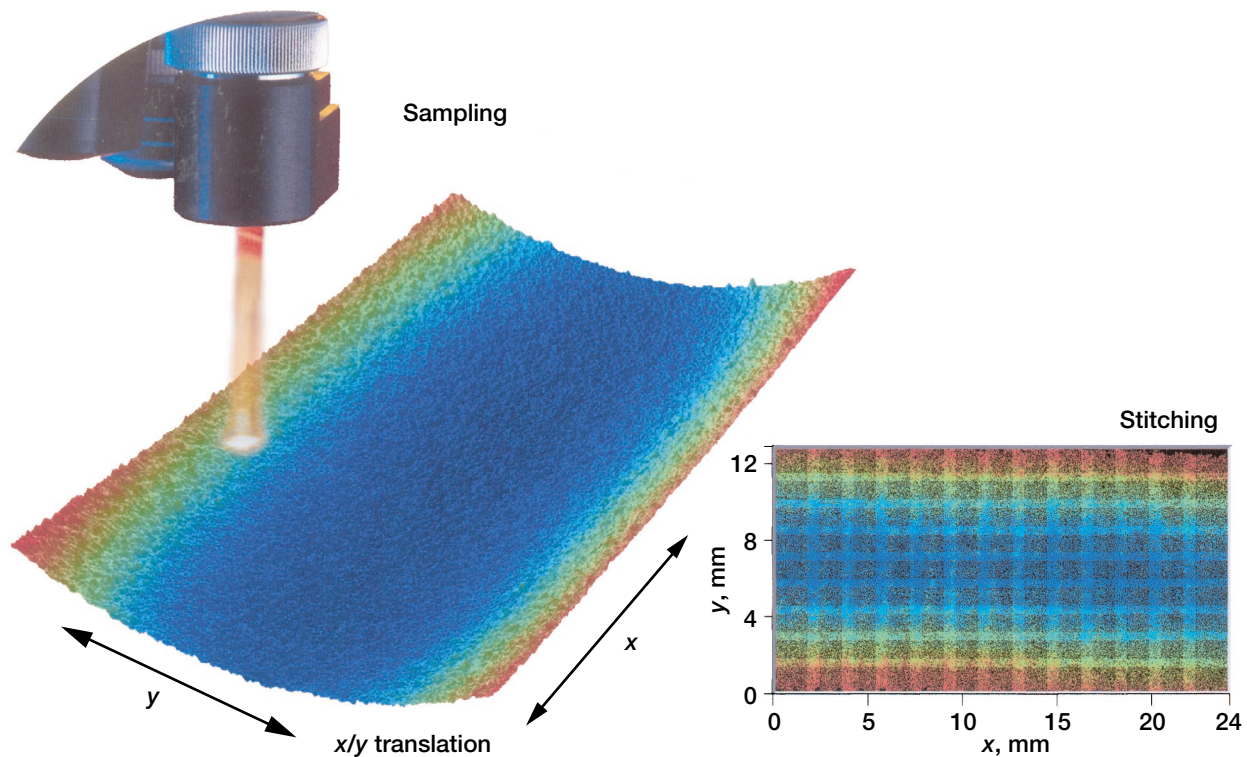


Figure 6.—View of sampling and stitching.

After erosion, the given area (12.5 by 18 mm) of the eroded specimen was again analyzed with the noncontact optical profiler (fig. 7(c)). The analyzed area was always larger than that of the erosion wear scar. The measurement data were stitched together to give a plot of the stitched area with surface statistics. The natural volume of the stitched area, in which the surface after erosion would hold if it were covered just to the nominal surface of the highest peak, was obtained (fig. 7(d)). In other words, the volume necessary to submerge the stitched area of the surface with an erosion wear scar was calculated. This calculated volume is designated V_2 in this investigation. Simply, the erosion volume loss (fig. 7(e)) can be expressed as the natural volume of the eroded surface minus the natural volume of the uneroded surface:

$$\text{erosion volume loss} = V_2 - V_1$$

Thus, in the stitching method, the erosion wear volume loss was derived from the volume analyses of the three-dimensional contour maps obtained before and after erosion. Examples of the three-dimensional contour maps of a coated vane coupon specimen before and after erosion are given in figures 8(a) and (b).

For the depth-measuring method, the erosion volume wear loss was obtained using the following equation:

$$\begin{aligned} \text{erosion volume wear loss} = & \text{mean erosion depth} \times \text{eroded area} + \text{net missing volume of eroded surface} \\ & - \text{natural volume of uneroded, bare surface} \end{aligned}$$

To obtain the average erosion depth of an eroded scar, the erosion depth was measured at eight locations, which are designated in figure 9(a) on an eroded specimen. At each location, noncontact, optical interferometry profiled the surface topography, which included the eroded and uneroded areas.

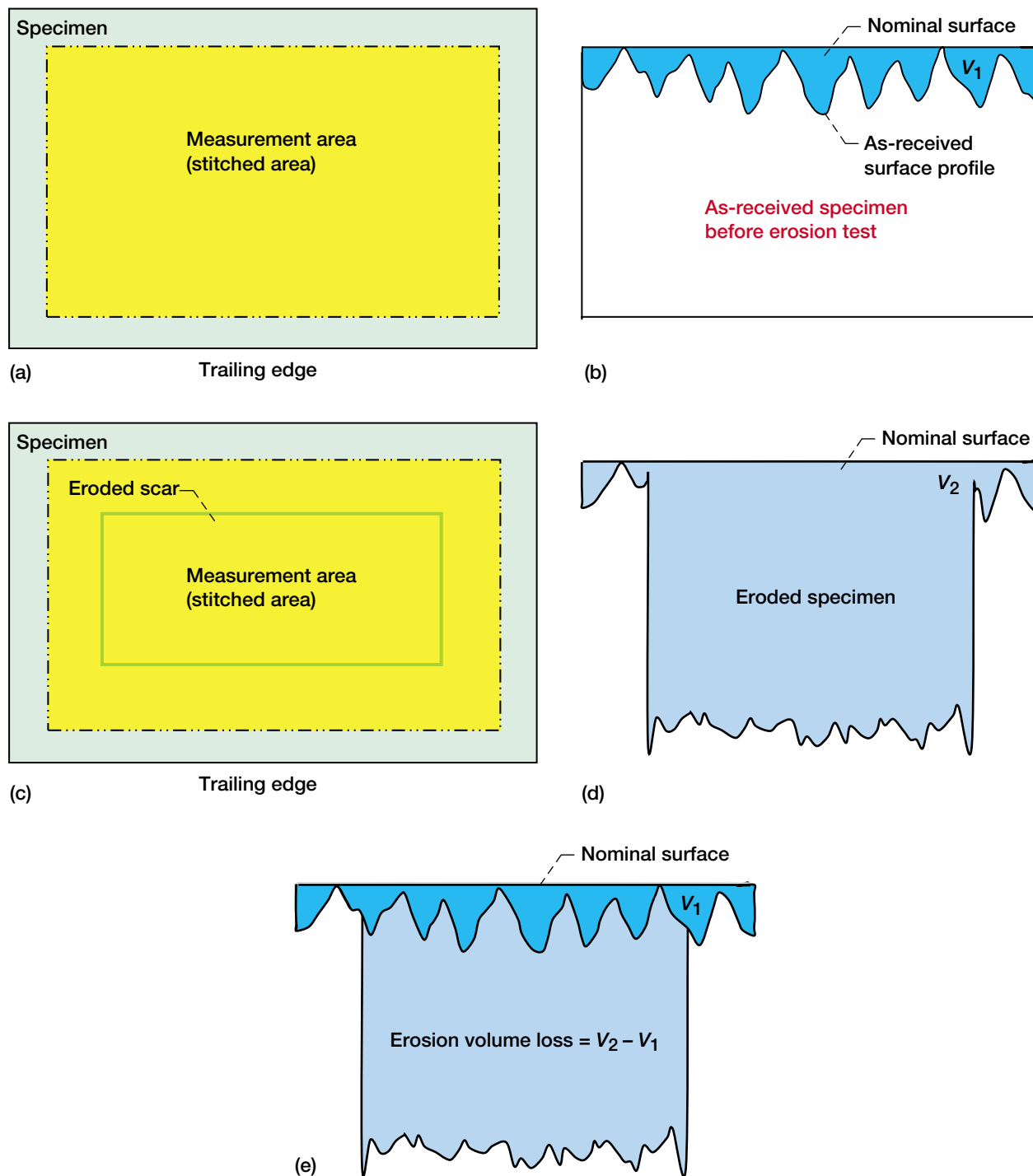


Figure 7.—Stitching method. (a) Measurement of uneroded specimen. (b) Natural volume, V_1 , of uneroded surface. (c) Measurement of eroded specimen. (d) Natural volume, V_2 , of eroded specimen. (e) Erosion volume loss.

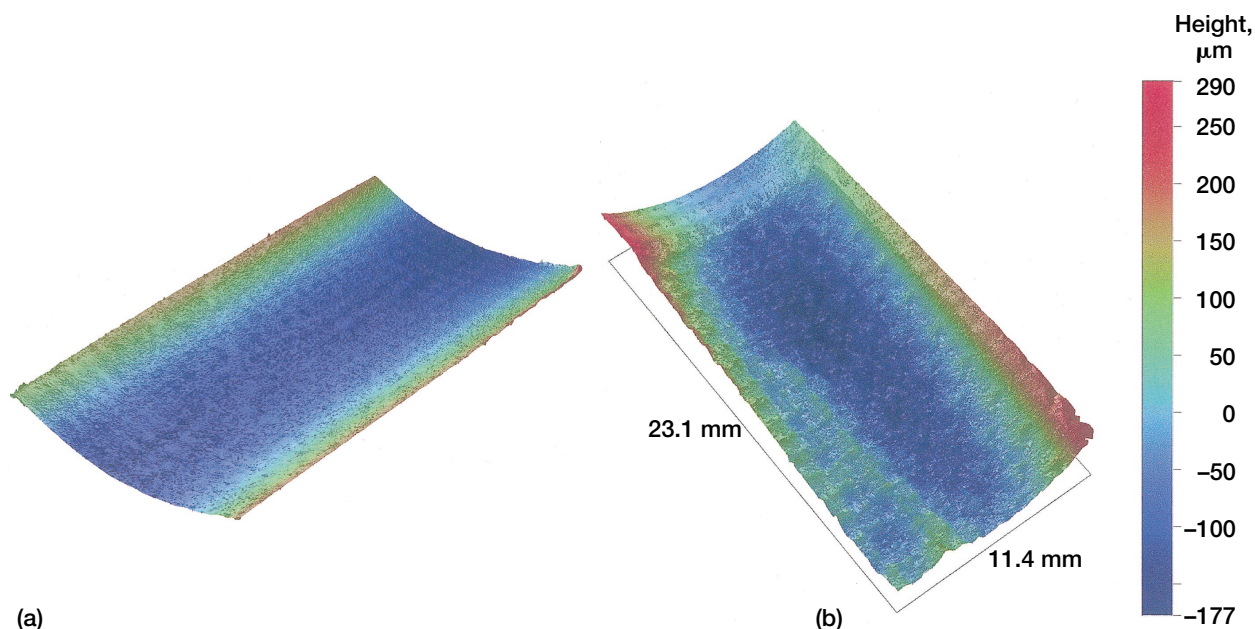


Figure 8.—Three-dimensional contour maps of coated specimen before and after erosion. (a) Uneroded, coated surface. Three-dimensional interactive display: three-dimensional contour map of the surface. (b) Eroded surface; impingement angle, 20°.

The uneroded area was used as a reference for the erosion depth measurement. Eight contour maps were obtained from each erosion scar. The maximum erosion depth was obtained by measuring a step height between a nominal surface and a zero level of the bottom wear surface of the erosion scar in a cross-sectional profile (a two-dimensional slice of a surface) of each contour map. Then, the mean value of the eight maximum erosion depths was determined and defined as the mean erosion depth (fig. 9(b)).

The eroded area was determined from measurements of the four sides of the rectangular-shaped erosion scar made using both an optical microscope with two micrometers and electronic digital calipers. The area of the eroded rectangle was expressed as the mean of the long side times the mean of the short side.

After erosion, the net missing volume of the eroded area was measured at eight random locations in the eroded wear scar. Then, the total net missing volume of the whole eroded area was calculated. The net missing volume is equal to the negative volume minus the positive volume in the eroded area (fig. 9(c)), where the negative volume is the volume above the bottom wear surface of an erosion scar and below the zero level, whereas the positive volume is the volume below the bottom wear surface of the erosion scar and above the zero level. In general, the negative volume is almost equal to the positive volume so that the net missing volume of the eroded area is negligible.

The natural volume of uneroded, bare surface was obtained before erosion (fig. 9(d)). The natural volume of uneroded, bare area was randomly measured at eight locations. Then, the total natural volume of the area, which is equal to the eroded wear scar area, was calculated.

Thus, the erosion wear volume loss, which is illustrated in figure 9(e), can be calculated as follows:

$$\text{erosion volume wear loss} = \text{mean erosion depth} \times \text{eroded area} + \text{net missing volume of eroded surface} \\ - \text{natural volume of uneroded, bare surface}$$

Examples of a three-dimensional view and two-dimensional, cross-sectional profiles of part of an erosion wear scar used for the erosion depth measurement are shown in figures 10(a) and (b). The noncontact, optical interferometer profiled the surface topography, which included the eroded and

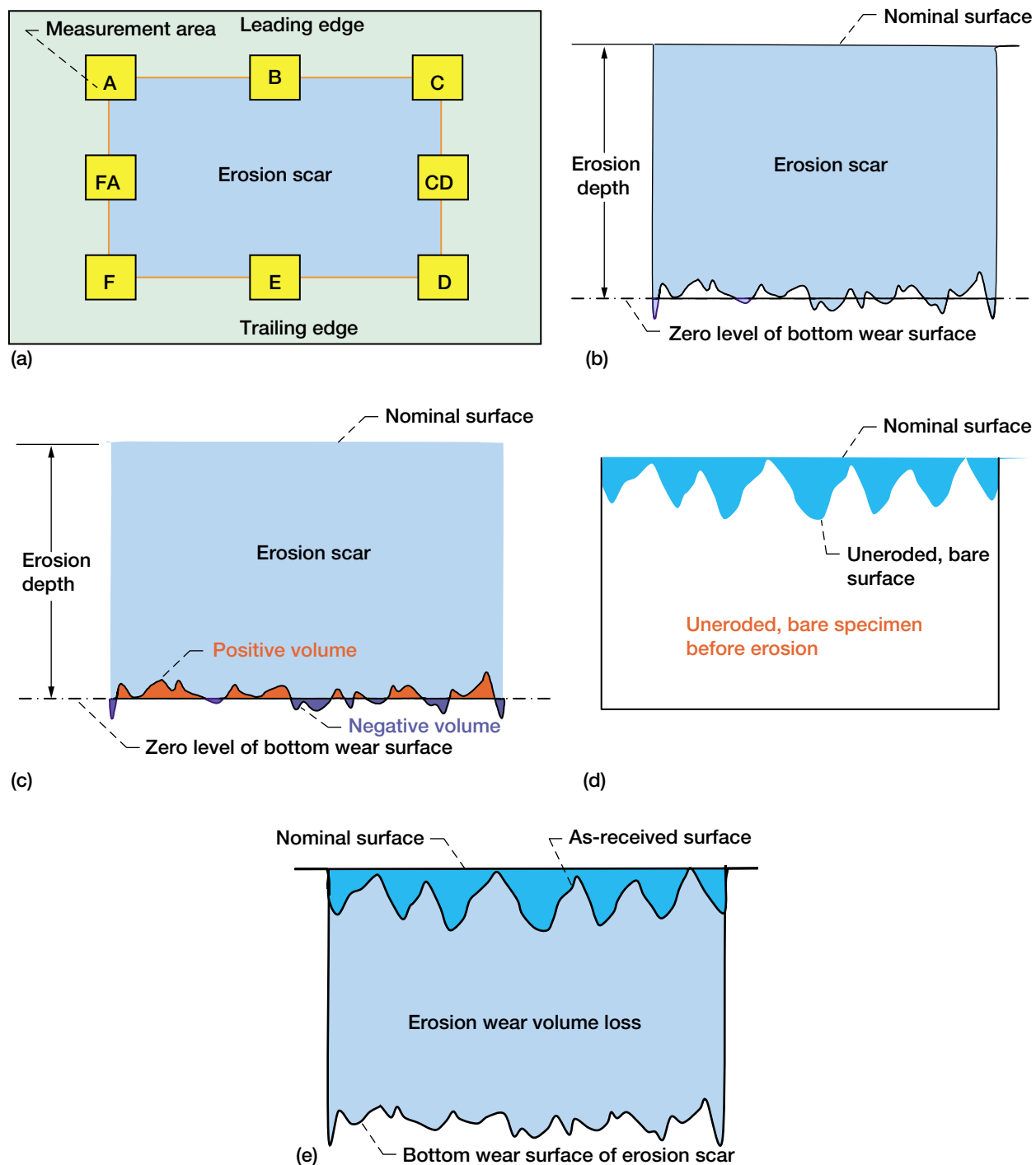


Figure 9.—Depth-measuring method. (a) Designation of sampling area. (b) Erosion depth. (c) Net missing volume of eroded area. (d) Natural volume of uneroded, bare surface. (e) Erosion wear volume loss.

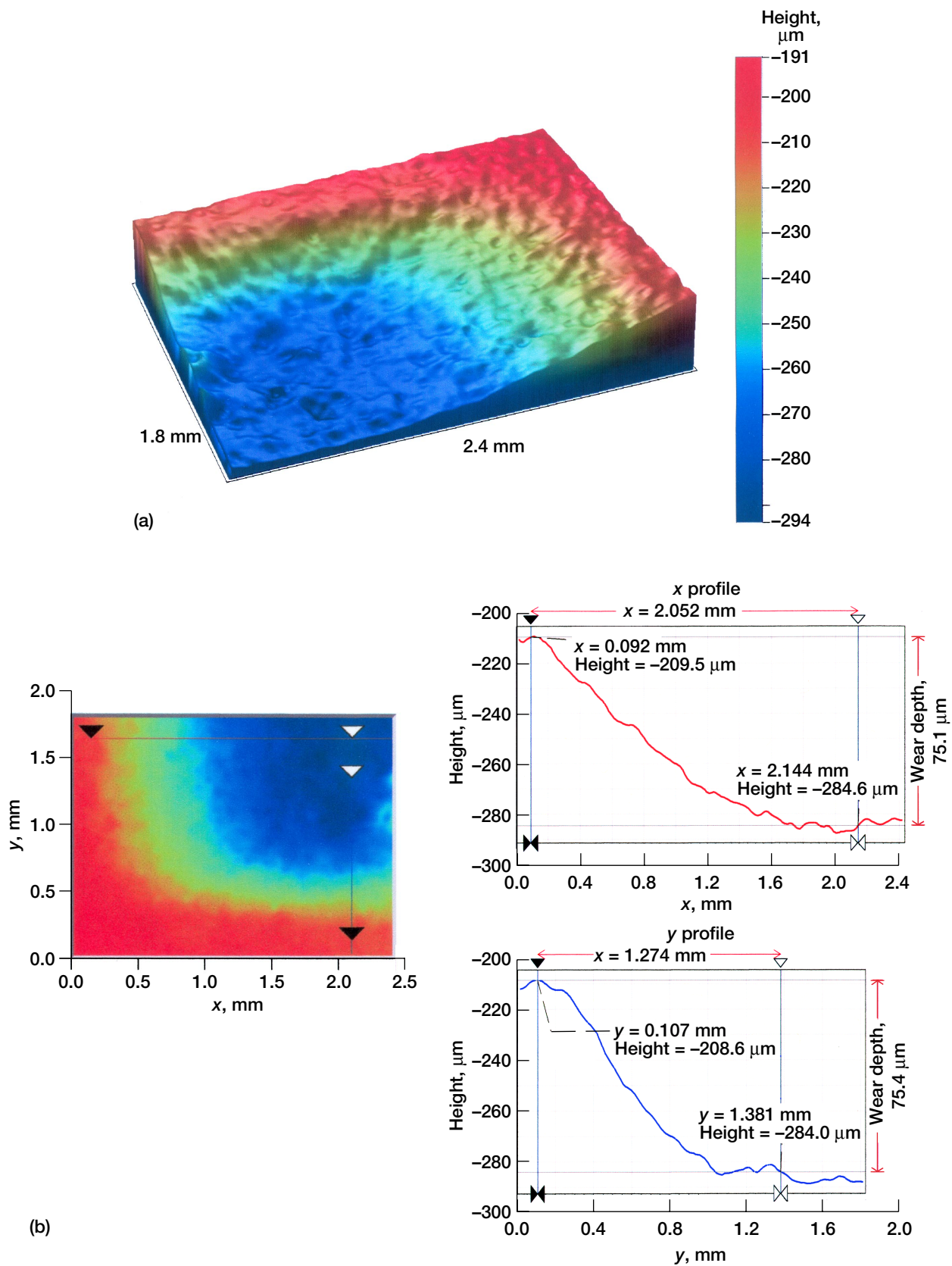


Figure 10.—Depth profiles of a coated specimen after erosion. (a) Three-dimensional contour map. (b) Two-dimensional contours showing erosion depths.

uneroded, bare areas. The maximum erosion depth was obtained by measuring a step height between a nominal surface and a zero level of bottom wear surface of the erosion scar in a cross-sectional profile (a two-dimensional slice of a surface) of each contour map (e.g., fig. 10(b)).

Results and Discussion

Comparison of Stitching and Depth-Measuring Method

Volume of measurement standard.—Figures 11(a) and (b) present the measured volume values of part of the groove and the whole rectangular groove in the step-height measurement standard, respectively. Their three-dimensional images are shown earlier in figures 4(a) and (b).

The data presented in figures 11(a) and (b) indicate that there is no difference in the volumes measured by the stitching method and the depth-measuring method. The standard deviations of the measured values were smaller than 1 percent of the measured mean values. Either method can be used to determine the rectangular groove volume. Since the stitched area is relatively small and the surface of the measurement standard is flat and smooth, the measurement time using the stitching approach is much about the same as that with the depth-measuring method.

Erosion wear volume loss measurement.—Figures 12(a) and (b) present, for impingement angles of 90° and 20°, respectively, the measured average values of erosion volume losses for the uncoated PMC, the 0.09-mm-thick WC-Co-coated PMC, and the 0.06-mm-thick WC-Co-coated PMC using the stitching and depth-measuring methods. The data presented in figures 12(a) and (b) indicate that there is no significant difference in erosion wear volume losses measured by the two methods. The difference in erosion wear volume loss is not significant because it is within 6 percent of the measured value and less than the standard deviation of each uncoated or coated PMC. The similarity of the values determined by the two methods means that the erosion wear loss over each erosion wear scar is very even.

Although both the stitching and the depth-measuring methods can be used for erosion volume loss measurements, the stitching method is relatively time-consuming because of the large area sampling and

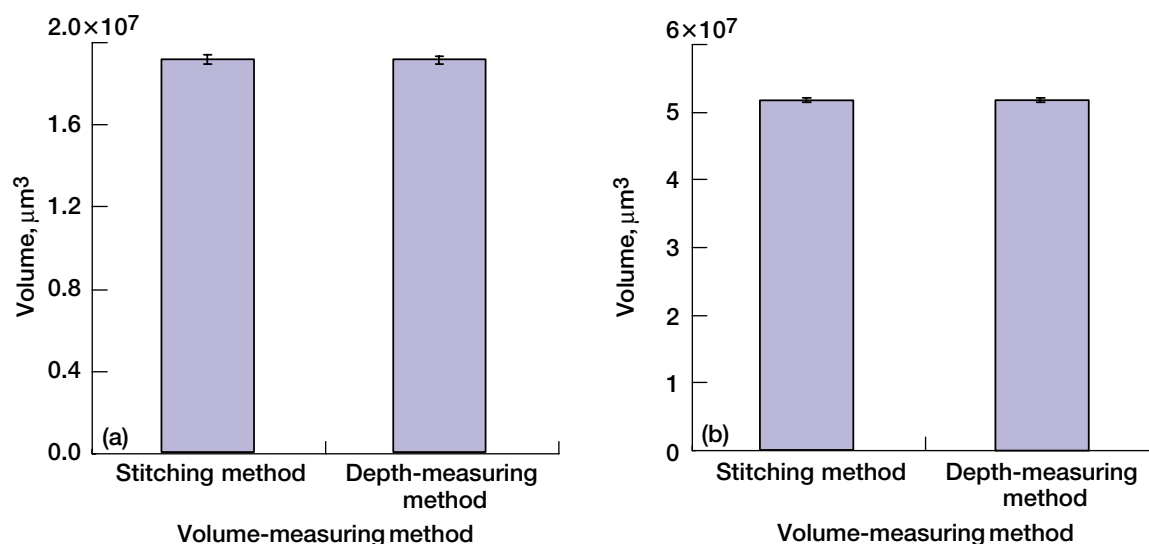


Figure 11.—Comparison of the volume of part and the whole rectangular groove formed in the step-height measurement standard. (a) Part of the rectangular groove. (b) Whole rectangular groove.

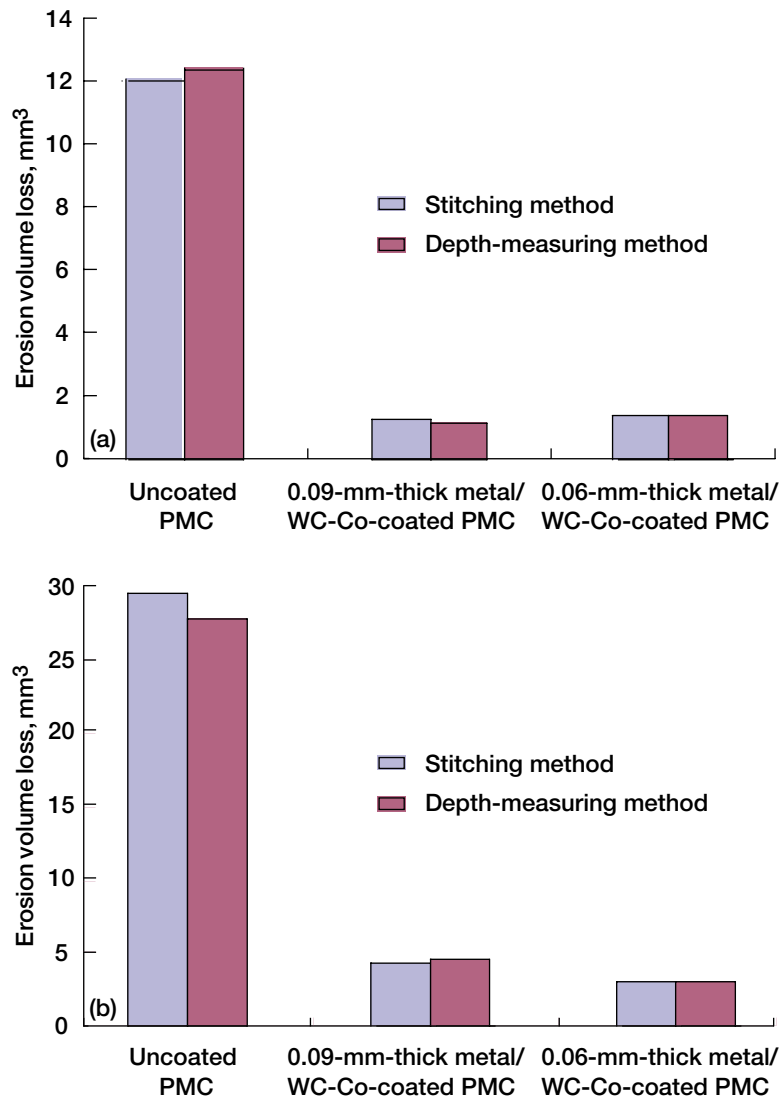


Figure 12.—Comparison of erosion wear volume losses of polymer matrix composites (PMCs) after impingement at 229 m/s and 383 K measured by the stitching method and depth-measuring method. (a) 90° impingement with 10 g of Arizona Road Dust (ARD) particles. (b) 20° impingement with 15 g of ARD particles.

measurement. The measurement time needed with the depth-measuring method can be a factor of 10, or more, less than that needed for the stitching method. Therefore, the simple depth-measuring method could be used to determine erosion volume loss.

Figures 12(a) and (b) also indicate that, in comparison with the erosion wear volume losses of uncoated, bare PMCs, the WC-Co coatings deposited on the PMCs markedly reduced the erosion wear volume loss: by a factor of 10 at an impingement angle of 90° and by a factor of 7 to 10 at an impingement angle of 20°.

Volume Wear Rate and Erosion Resistance

Figures 13(a) and (b) present the volume wear rate (volume removed per unit mass of erodent particles) and the reciprocal of the volume wear rate (a measure of erosion resistance), respectively, for the uncoated, bare PMCs, 0.09-mm-thick WC-Co-coated PMCs, and 0.06-mm-thick WC-Co-coated PMCs. The erosion wear volume losses were obtained from the stitching method. The volume wear rates of both uncoated and coated PMCs depend strongly on the impingement angle, as illustrated in figure 13(a), which shows a greater volume wear rate at an impingement angle of 20° that decreases to two-thirds to one-half of the volume wear rate at normal incidence. Furthermore, it is interesting to note that the volume wear rate does not depend on the coating thickness.

In comparison to the erosion resistance of uncoated PMCs (fig. 13(b)), the WC-Co coatings deposited on the PMCs markedly enhanced erosion resistance. The tenfold increase in erosion resistance will contribute to longer vane lives, reduced erosion-related breakdowns, decreased maintenance costs, and increased vane reliability, which could lead to overall economic savings.

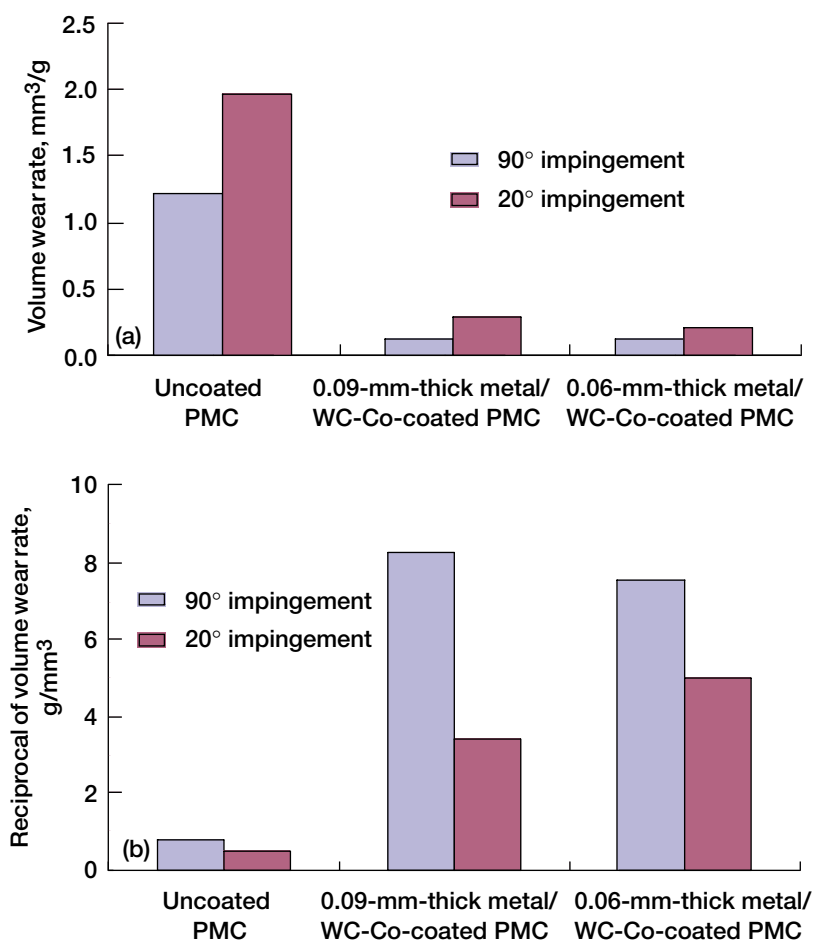


Figure 13.—Volume wear rate and erosion resistance for uncoated, bare polymer matrix composites (PMCs), 0.09-mm-thick metal/WC-Co-coated PMC, and 0.06-mm-thick metal/WC-Co-coated PMC subjected to impingement with ARD at 229 m/s and 383 K. (a) Volume wear rate. (b) Erosion resistance (reciprocal of volume wear rate).

Surface Roughness

The vane specimens inherently have cylindrical characteristics, as presented in figure 14(a) as an example. This figure shows all the surface data, including the cylindrical characteristics. Figure 14(b) shows the plot in which the cylindrical characteristics have been removed from figure 14(a). Removing the cylindrical characteristics causes the vane specimen to appear flat, so that surface features, particularly surface roughness, can be observed instead of the dominant cylindrical shape.

Figure 15 presents average roughness values of the uncoated and coated specimens before and after erosion. Before erosion, the surface roughness values of the uncoated, bare vane specimens was one-third of those of the coated specimens. However, the surface of the uncoated, bare specimens was roughened because of erosion. The surface roughness of the uncoated vane specimens increased to threefold of the original surface roughness after erosion. On the other hand, the surface of the coated vane specimens was smoothed. The surface roughness of the coated vane specimens was decreased nearly 10 percent.

The decrease in surface roughness of the coated vanes may be beneficial, lowering air friction, which will subsequently reduce energy consumption and costs.

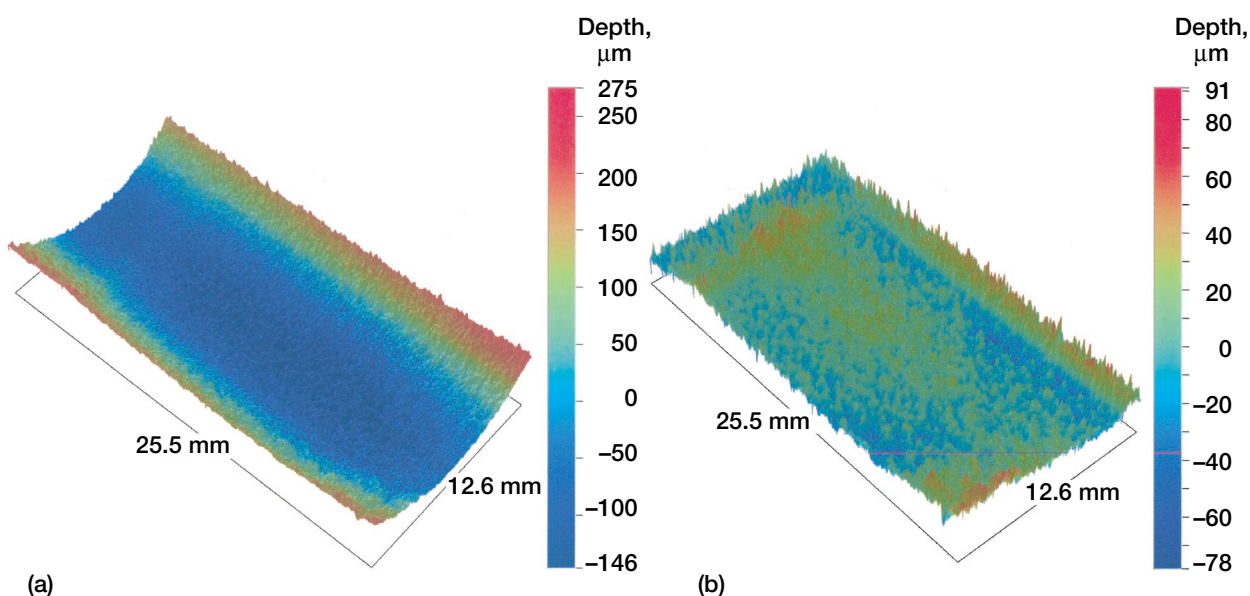


Figure 14.—Three-dimensional optical interferometry images of the eroded wear scar of a coated polymer matrix composite (PMC) sample obtained after an erosion test. The eroded surface appears as a large scar in the direction of the airstream containing abrasive particles. The erosion test was conducted at the University of Cincinnati with 15 g of ARD particles at an impingement angle of 20° and a velocity of 229 m/s at room temperature. (a) Three-dimensional display from measurement. (b) Three-dimensional display with cylindrical shape removed.

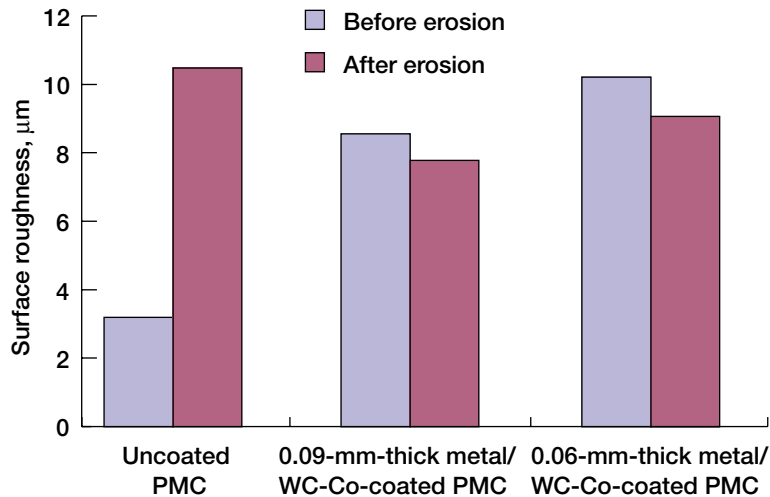


Figure 15.—Average roughness values, R_a , of uncoated, bare polymer matrix composite (PMC) specimens and coated specimens before and after erosion with 15 g of ARD particles at a 20° impingement angle, 229 m/s, and 93 °C.

Summary of Results

The following results were obtained from this investigation of the erosion volume loss of uncoated and coated polymer matrix composites:

1. There is no significant difference in erosion volume losses measured by the two methods. Either the stitching method or the depth-measuring method can be chosen for erosion volume loss measurements.
2. With the depth-measuring method, the measurement time is a factor of 10, or more, less than it is for the stitching method.
3. An even loss of substance occurred over each erosion wear scar during erosion.
4. The volume wear rates of both uncoated and coated PMCs depend strongly on the impingement angle, indicating a greater volume wear rate at a 20° angle and two-thirds to one-half of that at normal incidence.
5. The volume wear rate does not depend on the coating thickness.
6. The WC-Co coatings deposited on the PMCs markedly enhanced erosion resistance—by a factor of 10 at an impingement angle of 90° and by a factor of 7 to 10 at an impingement angle of 20°.
7. The surface of the uncoated, bare vane specimens was roughened. Erosion increased the surface roughness of these specimens to threefold of their original roughness. On the other hand, the surface of the coated specimens was smoothed by erosion. The surface roughness of the coated vane specimens decreased nearly 10 percent. After erosion, the coated vane specimens were smoother than the uncoated vane specimens.

Concluding Remarks

Noncontact, optical interferometry can be used to accurately determine the erosion wear volume loss of PMCs with multilayered structures while preserving the specimens. Two methods, the stitching method and the depth-measuring method, of determining erosion wear volume loss using noncontact, optical interferometry were evaluated in this investigation. Although either method can be used for erosion wear volume loss measurements, the stitching method is relatively time-consuming because of the large area that is sampled and measured. Instead, the simple depth-measuring method could be used to determine erosion wear volume loss.

The two-layered (WC-Co topcoat and metal bondcoat) coatings for PMCs remarkably reduced the erosion volume loss by a factor of approximately 10. The tenfold increase in erosion resistance will contribute to longer vane lives, lower air friction, reduced related breakdowns, decreased maintenance costs, and increased vane reliability. The decrease in the surface roughness of the coated vanes may be beneficial because it will lead to lower air friction and, subsequently, reduce energy consumption. Eventually, the coatings could lead to overall economic savings.

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